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Direct observation of two-level electronic emission from QDs InAs/GaAs by means of C–V and admittance spectroscopy

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Abstract. The emission of electrons from ground and first excited energy levels of InAs self-organized quantum dots grown by MOCVD has been registered by means of steady-state capacitance vs. voltage technique and admittance spectroscopy. We found a fine structure of carrier concentration profile in the area of QDs. The dependence of activation energy of the levels in the QDs on applied bias also has been obtained.

Introduction

There has been considerable interest at present in studying of electronic properties of quantum dot (QD) heterostructures InAs/GaAs, suitable for fabricating laser diodes emitting at 1.3 μm [1, 2]. Optical methods (PL, PLE) have been commonly used for getting information about the optical transients between energy levels inside the quantum dots [1, 3], but these methods do involves both electron and hole subsystems, so one can not obtain the absolute values of quantized energy levels.

Capacitance spectroscopy (and admittance spectroscopy as its modification) makes it possible to test separately either electron or hole emission mechanism, as well as the precise obtaining of concentration, geometric parameters and energy band discontinuities have became possible. In this work we present the results of admittance and capacitance measurements of p-n- heterostructures InAs/GaAs with self-organized quantum dots, which directly indicate the emission from ground and first excited electron levels.

Experimental results and discussion

The structures were grown by MOCVD (metal-organic chemical vapor deposition) on highly n^+-doped GaAs substrate, followed by Si-doped buffer layer. The array of quantum dots consisted of three sheets of vertically coupled InAs QDs was spaced with 2.8-nm undoped GaAs layers. The structures were capped with 448-nm GaAs layer, and then 650-nm thick p-GaAs layer was deposited to create p-n junction (Fig. 1). Details of growth and device fabrication see in Ref. [4].

The measurements were performed using HP4284A RLC meter in the range of frequencies 1 kHz. . . 1 MHz and temperatures 10–300 K. The amplitude of measuring signal was 10 or 50 mV.

The C–V-characteristics of the sample have an inherent for quantum wells and QDs plateau in the range of reverse biases $-1.0 \div -3.0$ V (Fig. 2). The width of the plateau increases permanently when the temperature goes down to 10 K.

This behavior indicates the growth of electron charge inside the QDs with temperature lowering due to enhancement of energy barriers. We didn't observe the suppressing of the plateau for temperatures below 80 K, as was reported in [3, 5] for Shottky barriers with InAs quantum dots, but grown by molecular beam epitaxy (MBE).

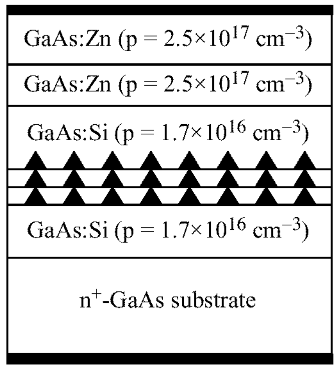

Fig. 1. Layer sequence of p-n structure with self-organized InAs quantum dots [4].

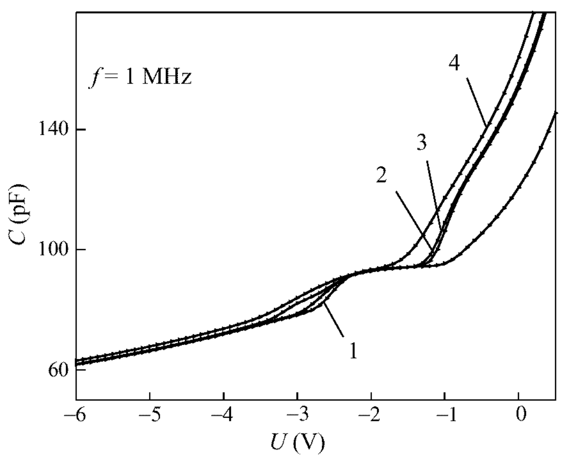

Fig. 2. C–V characteristics of the structure with InAs QDs at the temperatures: 1—10 K; 2—45 K; 3—80 K; 4—200 K.

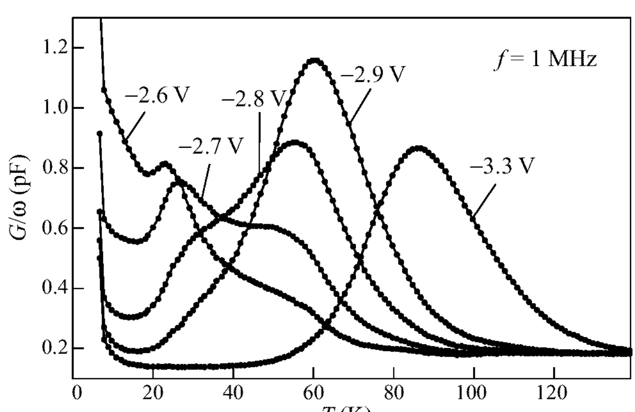

Fig. 3. The admittance spectra of the structure as a function of applied reverse bias.

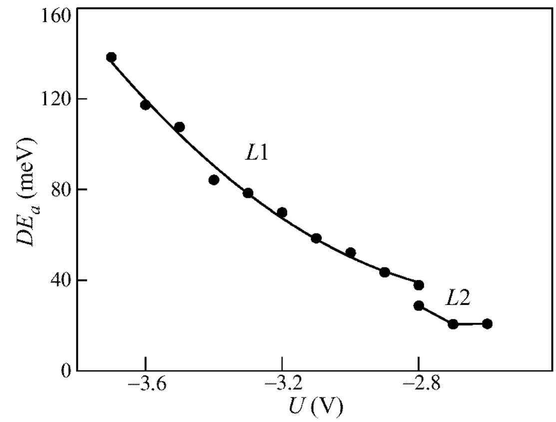

Fig. 4. Dependence of "apparent" activation energy of ground (L1) and first excited (L2) levels in the QD on reverse bias.

After ending the plateau (approximately at $|U| > 2.2$ V) a step in C–V characteristics was observed. This step corresponds to the strong energy bands bending in applied electric field when the conditions for thermionic emission of electrons from the QDs fulfill. It may be registered with the help of admittance spectroscopy. The spectra of admittance spectroscopy have been measured at frequencies from 1 kHz up to 1 MHz. We detected the QDs response in the range of reverse biases $-2.2 \ldots - 3.7$ V. A set of spectra for different applied biases is shown in Fig. 3. At high electric fields ($|U| > 3$ V) there was a single peak in admittance spectra. It's amplitude and temperature maximum had strong dependencies on frequency and bias. With reducing of reverse bias a second, additional, peak was appeared at the low temperature side of the spectra, which, in turn, had his own frequency and bias behaviors. We attribute these peaks to the emission of carriers from the ground and first excited levels in the QD. At $U = -2.7$ V the two peaks are about equal to each other.

Determined from Arrenius plot the "apparent" ionization energy of the levels L1 and L2 depended considerably on U_{rev} (Fig. 4). The energy of L1 level changed 3 times. This phenomenon is well known for DLTS and admittance measurements of structures with quantum wells and quantum dots. The reason of it is the changing of the electrostatic potential at different applied biases and following modification of electron energy spectrum inside the QD.

The second reason, as was pointed by D. V. Lang [6], may be the competing mechanisms of thermal activation and thermally independent tunneling from the level. Actually the tunneling mechanism dominated in DLTS spectra of the same samples at low temperatures in Ref. [4, 7].

When calculating the apparent concentration profile $n = f(w)$ using conventional differentiation of C–V characteristics we found a fine structure of concentration peak in vicinity of the QDs layer, Fig. 5(a). (The plots were built in coordinates $n - U$, which is more convenient in this case due to nonlinear dependence $w = f(U)$). The fine structure was detected only at low frequencies in the range of temperatures 40–80 K (In contrast see Fig. 5(b), where no fine structure is observed). We guess this fine structure was created by the symmetrical and asymmetrical wave functions of the ground (L1) and first excited (L2) energy levels of electrons in the QD. This suggestion is in agreement with the results of admittance spectroscopy.

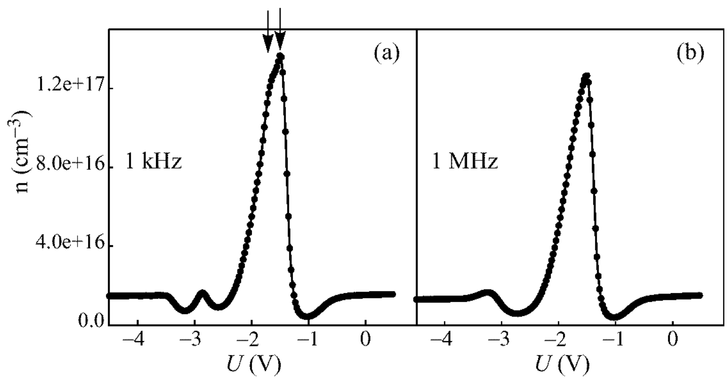

Fig. 5. N-U characteristics of the structure with the QDs at different frequencies. $T = 45$ K.

There also noticed another small peak (positioned at $U = -2.8$ V) in the low frequency concentration profile (Fig. 5(a)). One may explain its origin following [5] as due to modulation by testing AC signal the charge at the edge of the space charge region far from the QDs location.

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